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LOCAL CURRENT TRANSPORT AND CURRENT SHARING BETWEEN FILAMENTS IN STRIATED COATED CONDUCTORS WITH ARTIFICIAL DEFECTS (POSTPRINT)

C. Kwon, J.L. Young, and R.G. James

California State University

George A. Levin, Timothy J. Haugan, and Paul N. Barnes

Mechanical Energy Conversion Branch
Energy/Power/Thermal Division

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C. Kwon, J.L. Young, and R.G. James (California State University)
George A. Levin, Timothy J. Haugan, and Paul N. Barnes (AFRL/RZPG)

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California State University
Department of Physics and Astronomy
Long Beach, CA 90840

Mechanical Energy Conversion Branch (AFRL/RZPG)
Energy/Power/Thermal Division
Air Force Research Laboratory, Propulsion Directorate
Wright-Patterson Air Force Base, OH 45433-7251
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14. ABSTRACT
Multifilamentary YBCO coated conductor with fishnet striation pattern is investigated by transport measurements and scanning laser microscopy (SLM). Each filament is clearly visible in SLM images, and higher current flows along the edges of filaments. After initial measurements, an incision is made to disable two filaments and to investigate the changes in the current transport, the current sharing, and the dissipation patterns. Current sharing and redistribution are clearly observed among the filaments and at the weak links. We find that the dissipation is mainly caused by local current crowding. Since the current is to be shared among intact filaments, the most impacted area is the filaments closer to the disabled ones which have to carry higher current. The other susceptible area is the weak links where the current redistributes and the increased current density is expected.

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Local Current Transport and Current Sharing Between Filaments in Striated Coated Conductors With Artificial Defects

C. Kwon, J. L. Young, R. G. James, George A. Levin, Timothy J. Haugan, and Paul N. Barnes

***Abstract*—Multifilamentary YBCO coated conductor with fishnet striation pattern is investigated by transport measurements and scanning laser microscopy (SLM). Each filament is clearly visible in SLM images, and higher current flows along the edges of filaments. After initial measurements, an incision is made to disable two filaments and to investigate the changes in the current transport, the current sharing, and the dissipation patterns. Current sharing and redistribution are clearly observed among the filaments and at the weak links. We find that the dissipation is mainly caused by local current crowding. Since the current is to be shared among intact filaments, the most impacted area is the filaments closer to the disabled ones which have to carry higher current. The other susceptible area is the weak links where the current redistributes and the increased current density is expected.**

***Index Terms*—Dissipation pattern, filamentary coated conductor, scanning laser microscopy.**

I. Introduction

THE second generation high temperature superconducting wire based on YBCO can currently satisfy some of performance requirements for high power applications. However, the large geometric aspect ratio in coated conductor (CC) design causes large hysteretic loss in ac and poses a major problem in the applications which require operating in ac field such as generators. Several design ideas have been proposed in order to reduce ac loss [1]–[3]. Carr and Oberly have divided the YBCO coated conductor cables into long filamentary strips with a little twist to reduce ac loss [1]. Cobb *et al.* used laser ablation to create striated epitaxial YBCO film and demonstrated the decrease in ac loss [4]. However, without the means to redistribute current in such geometry, a single defect can cause a catastrophic failure of the whole wire. In order to provide current sharing, it is proposed that striations are interrupted to provide weak links between filaments [5].

It has been shown that the multi-filamentary samples with inter-filament bridging as weak links have lower ac losses than unstriated samples, even though the loss is higher than the fully striated samples [6]–[9]. The weak links generally increase ac loss, and the degree of increase depends on the placement and physical property of weak-links. Hence, the design optimization of the geometry and properties of weak-links is needed for the practical use of filamentary CC wires. The first design requirement is the reduction of ac loss. Another is to optimize for current redistribution if current blockage occurs in a filament. Since reducing ac loss and increasing current sharing are conflicting requirements, the final design will need a compromise. In addition, feasibility, cost, stability, and quench protection have to be considered for the final design.

We have demonstrated that the local maps of transport current and superconducting dissipation can be obtained using SLM [10]. In this work, our objectives are to study how current sharing and redistribution occur in multi-filamentary CCs. In order to do that, we have created an incision to disable filaments in a sample and studied how local current transport and dissipation patterns are modified.

In this paper, a fishnet patterned multi-filamentary CC sample is studied. The sample is characterized with transport and SLM techniques in the original state. Afterward, an incision is made to cut two filaments and the sample is characterized again. The redistribution of current at the weak links is clearly observed. After the cut, the filaments neighboring the disabled ones are carrying higher current and show the dissipation first. The increased current density at the weak links also makes them susceptible for the early dissipation. We conclude that the current crowding is the main factor limiting the current carrying capability of this sample.

II. Experiment

Striations in multiply connected CCs are made by laser micromachining to create long filaments with weak links. The different patterns are named after the placement of weak links [9]. In this paper, we have studied a fishnet pattern sample.

After receiving the sample, the top silver layer is etched to expose YBCO and the sample is prepared for four-probe transport measurements by depositing gold contacts. Extra care was taken to ensure good gold coverage over each striation in the sample to establish uniform contact resistance among the strips. The bias current was applied along the direction of the striations. Detailed information about SLM and our setup can be found in the earlier publications [10], [11].

The sample is measured using conventional transport and SLM techniques. Two modes of SLM were used for this sample; variable temperature scanning laser microscopy (VTSLM) and

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C. Kwon, J. L. Young, and R. G. James are with the Department of Physics and Astronomy, California State University, Long Beach, CA 90840 USA (e-mail: ckwon@csulb.edu; jyoung4@csulb.edu; rjames@csulb.edu).

G. A. Levin, T. J. Haugan, and P. N. Barnes are with the Air Force Research Laboratory, WPAFB, OH 45433-7919 USA (e-mail: george.levin@wpafb.af.mil; timothy.haugan@wpafb.af.mil; paul.barnes@ wpafb.af.mil).

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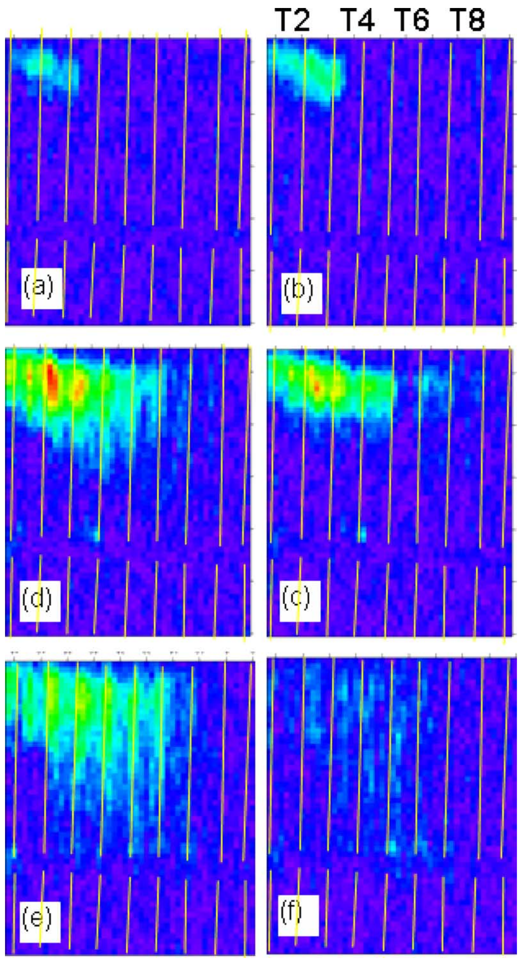

Fig. 1. A series of VTSLM taken from the original sample using $I_B = 70$ mA at (a) 90.2 K, (b) 90.3 K, (c) 90.4 K, (d) 90.6 K, (e) 90.8 K, and (f) 91.0 K. The fishnet pattern is overlaid on the images. The width of each filament is 0.5 mm and the weak link openings are 0.3 mm.

low temperature scanning laser microscopy (LTSLM) [12]. In VTSLM mode, a fixed current is applied (I_B) and SLM image is taken by varying temperatures near the superconducting transition. In LTSLM mode, the sample temperature is fixed at $T < T_c$ and SLM image is taken while the bias current is increased above I_c.

After the initial measurements, an incision is made to cut two filaments off to disable them using a LaserScissors Pro 300 Workstation mounted in Olympus microscope. The sample is characterized again to study how disabled filaments modify current transport and dissipation patterns.

III. Results and Discussion

Fig. 1 is a series of VTSLM images taken from the fishnet striated sample.

The striation pattern taken from a photodiode image is overlaid on some images as a guide to the eyes. There are nine filaments at the top and the bottom. The top and bottom filaments are connected directly through openings placed around 2/3 way down to provide superconducting weak links.

Most of the features are concentrated at the top filaments. As we reported earlier, the signal intensity (δV) of VTSLM images is proportional to (dR/dT) and the local current density (J_B) [10], [11]. Hence, ΔV is the highest at the temperature (T_c^*) when the resistance drop (dR/dT) is the largest and decreases rapidly around that temperature.

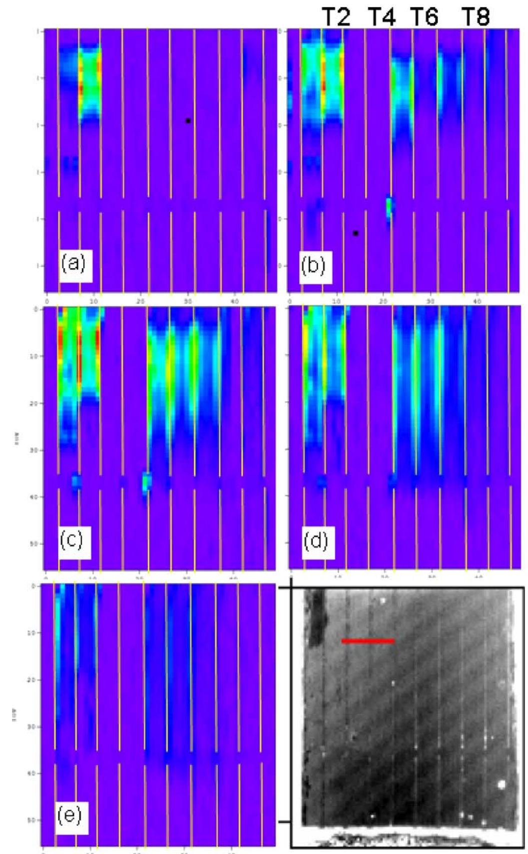

Fig. 2. A series of VTSLM images taken after two filaments are cut. The images are taken at (a) 88.8 K, (b) 89.0 K, (c) 89.2 K, (d) 89.4 K, and (e) 89.6 K using $I_B = 100$ mA. The last figure is the photodiode image taken at the same time. A line is drawn to emphasize the position of the incision.

There is a slight variation of T_c^* in the sample as seen from Fig. 1. Most visible areas have T_c^* of 90.6 K. The center of the image including the weak links, T3, T4, T5, and T6 has T_c^* at 90.8 K. T7 has two T_c^*s at 90.4 K (the center) and 90.8 K (the top). We believe the small variation T_c^* does not have affect the overall current flow trend since no direct evidence is observed.

Even though it is not shown, LTSLM images taken at 0.5 K below T_c using higher current $(I_B = 190$ mA$)$ is similar to Fig. 1(a).

Since I–V starts to deviate from a linear behavior below 90.6 K, the sample is considered to be in the critical state. Hence, it is expected to see the similarity between the dissipation map taken using LTSLM and VTSLM images taken when I–V is non-linear.

One more noticeable feature in VTSLM images is the appearance of stronger ΔV along the striations. It is more distinct in Fig. 2. Fig. 2 is a series of VTSLM images taken after an incision was made to sever two filaments (T3 and T4). Each striation is clearly visible; hence there is no need for the overlaid pattern. The stronger ΔV at the edges of a filament than in the middle is why the striations have distinct appearance. Earlier we have discussed slight variation of T_c^* along some filaments, but not across the width of filaments. We can presume that ΔV

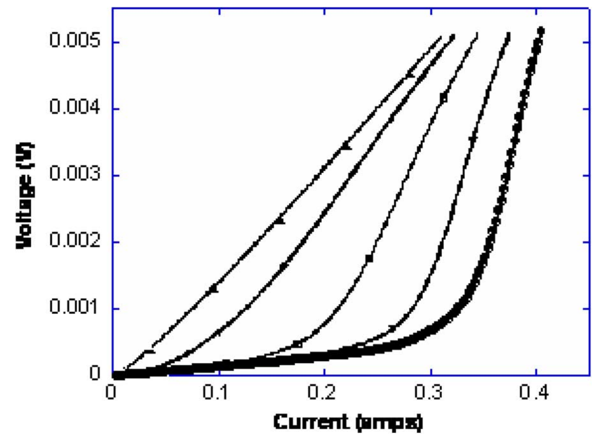

Fig. 3. I–V characteristics measured at $T = 89.8$ K, 89.4 K, 89.0 K, 88.6 K, and 88.2 K.

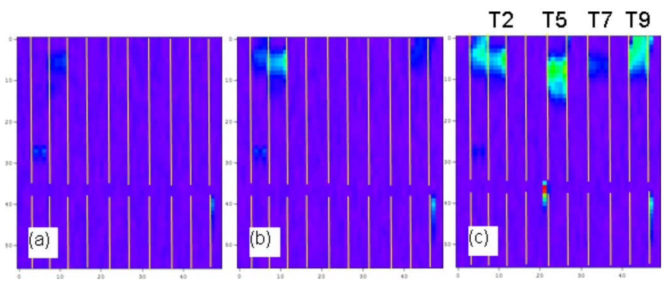

Fig. 4. LTSLM images measured at 88.2 K using I_B of (a) 220 mA, (b) 260 mA, and (c) 280 mA.

across the width of the filaments is related to the current density. Hence, we can conclude that higher current flows at the edges than the middle of filaments.

Fig. 3 is I–V characteristics measured between 89.9 K and 88.2 K. It clearly shows non-linear behavior below 89.4 K, even though there is a measurable voltage across the sample at $I_B = 100$ mA. It confirms that some VTSLM images are taken in the mixed states.

A theoretical analysis of the critical state behavior in type-II superconducting thin films has shown that the entire width of the film carries current while higher current density flows along the edges [13]. That explains the higher current density along the edges than the middle of a filament is originated from the critical state behavior. The combination of high ΔV along the striation and low ΔV inside makes each striation a landmark in SLM images and helps us to locate and identify other features.

Fig. 4 is a series of LTSLM images taken at 88.2 K. As we discussed earlier, LTSLM images showing the dissipation pattern are similar to VTSLM images taken at lower temperatures. This is somewhat expected because LTSLM images are taken near T_c and VTSLM images are taken in mixed states. The important question is whether the dissipation map will change far below T_c. Since SLM technique forces the sample to be near the critical state (by applying current close to I_c or doing the measurement near T_c), it is not clear whether the major change of dissipation pattern will occur at lower temperatures. A new mode of SLM is under development to enable LTSLM measurements at the lower temperatures, which will help answering the question.

SLM images are clearly different before and after the cut. The first thing to notice is the absence of ΔV signal in the two cut off filaments (T3 and T4). It seems that T3 and T4 do not carry current after the cut. T3 and T4 are visible in Fig. 1 confirming current flows in them before the incision is made. After the cut, there is not only no measurable ΔV in T3 and T4 but also significantly increased ΔV in the neighboring filaments (T2 and T5). As discussed earlier, the magnitude of ΔV is proportional to the current density when T_c is uniform. Hence, we can conclude that the cut off filaments (T3 and T4) do not carry current, and the nearest neighbor filaments (T2 and T5) have a burden of carrying higher current. It is substantiated by Fig. 4(c) where T2 and T5 dissipate early because of the increased current density.

Even in the original sample, ΔV is visible around the weak links [Fig. 1(e)] indicating that they are providing channels for current to redistribute as intended. After the cut, the signal ΔV is stronger at the weak links near the cut-off filaments [Fig. 3(c)] supporting the current redistribution at the weak links. Unintended consequence is that the increased current density creates current crowding at the weak links making them susceptible for early dissipation as shown in Fig. 4(c).

An earlier paper by Abraimov *et al.* [14] shows that the strong dissipation is observed where the cross sectional area of current transport is reduced and the local current density is high in an epitaxial YBCO film on SrTiO3 substrate. In the fishnet pattern striated CC sample studied, we also find that the increased local current density is the most important factor in the dissipation. The current crowding can occur in the neighborhood of the disabled filaments and the weak links where current redistributes.

One more thing to note in this sample is the lack of visible features at the bottom filaments. After reviewing all images, we conclude that one of the top filaments (T8) does not carry current. No visible signal is observed from T8 in the original sample. Even after two filaments are cut and current density is increased in other top filaments, T8 is still not visible in Figs. 2 and 4. Since T8 does not carry current, current density is higher in the top filaments than the bottom ones from the beginning. This provides a plausible explanation why the features are concentrated at the top filaments.

Lastly, Fig. 4 shows a strong dissipation in multiple filaments around the cut (T1, T2, and T5), but the intensity of δV decreases rapidly even before it reaches the weak links. We believe this is due to the current leakage to the neighboring filaments and the substrate via melted and splashed Hastelloy during the ablation process. Levin *et al.* [9] reported the existence of Hastelloy splash created during the laser micromaching which can provide an electric connection among silver overlayer, YBCO, and substrate. They indicate the higher than expected ac loss is due to the current flowing through the Hastelloy splash in the multifilament striated samples with weak links.

The premature disappearance of δV is also observed in Fig. 2, even though δV is visible in larger areas than Fig. 4. The difference between Figs. 2 and 4 can be explained with the conductivity of filaments; i.e. the neighboring filaments have higher conductivity in superconducting state than in the transition region, hence the current leaks easily to the neighboring filaments resulting in the reduced current crowding area. Our results may indicate the possibility of current leakage via Hastelloy splash in dc transport.

IV. Conclusions

A multi-filamentary YBCO coated conductor with a fishnet patterned striation is studied by scanning laser microscopy (SLM). VTSLM images show that the striations restrict current within the filaments. As intended, the weak links act as a place to redistribute the current among filaments. In the superconducting state, the main dissipation in the sample occurs at the filaments neighboring the cut-off ones and at the weak links instigated by the current crowding. Our study shows the importance of optimizing striation patterns for current sharing and redistribution as well as ac loss.

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